Vapour shielding of tin under intense plasma bombardment

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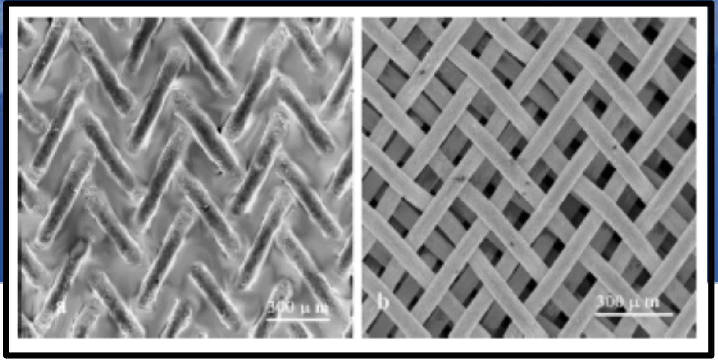
DIFFER, Eindhoven, The Netherlands



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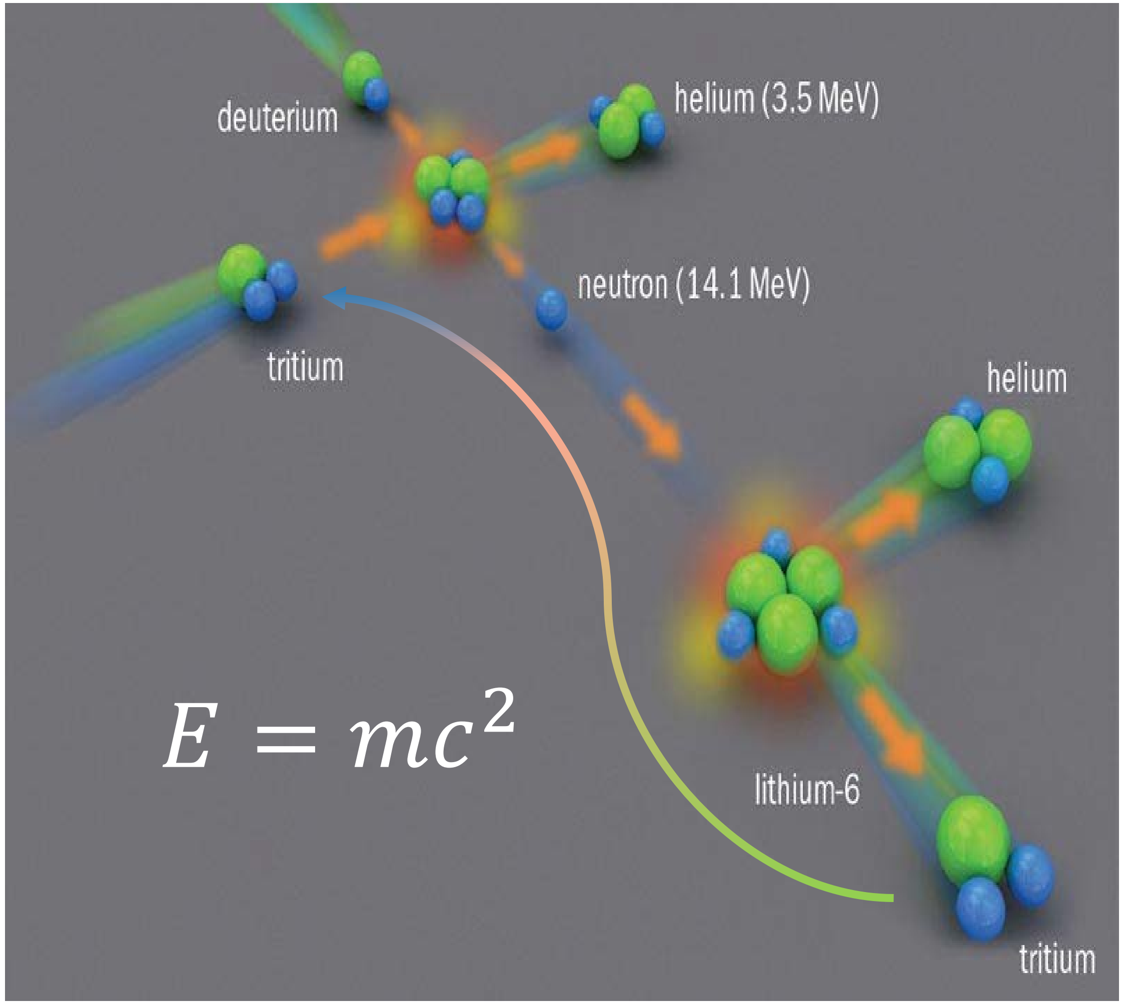
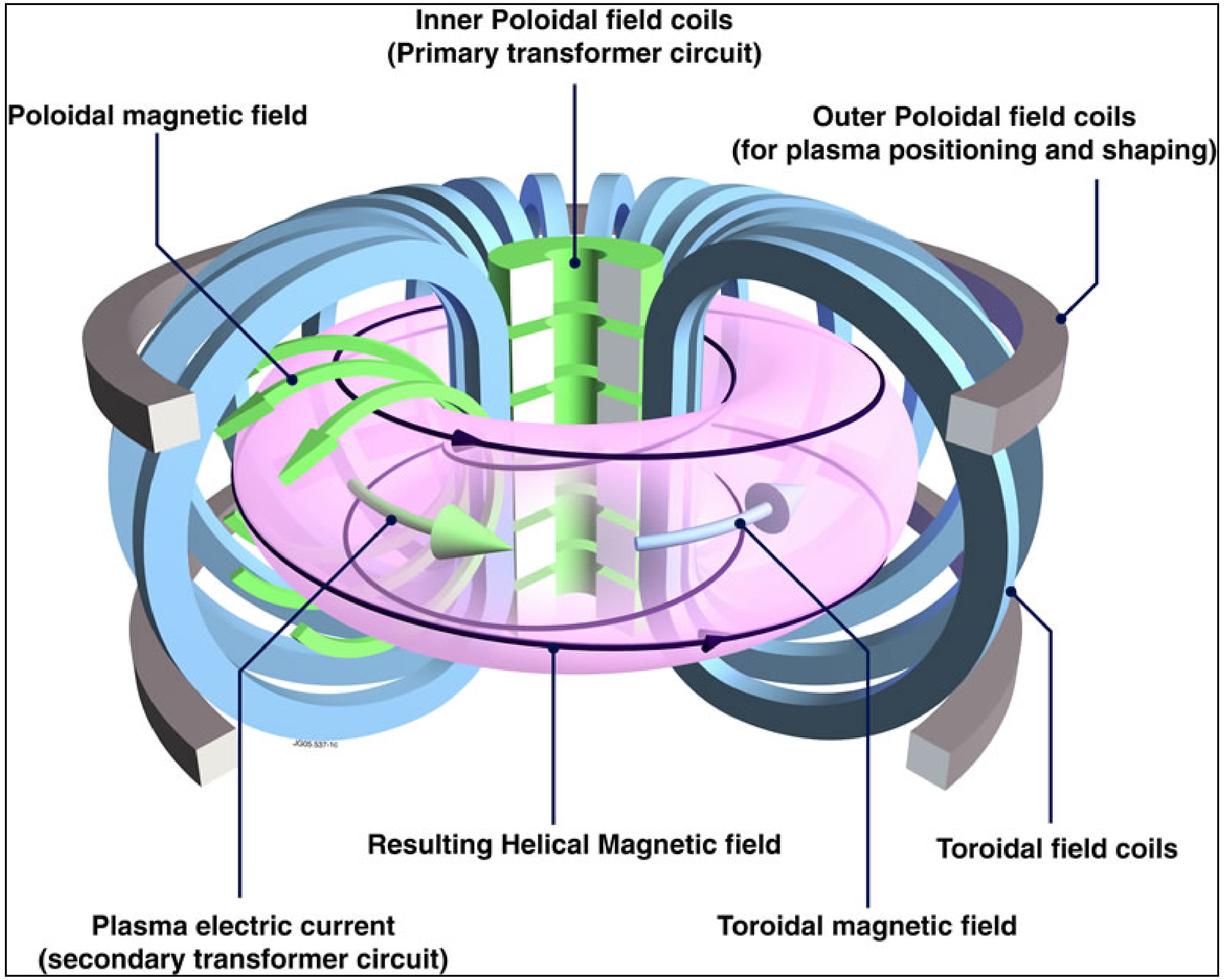
Fusion energy

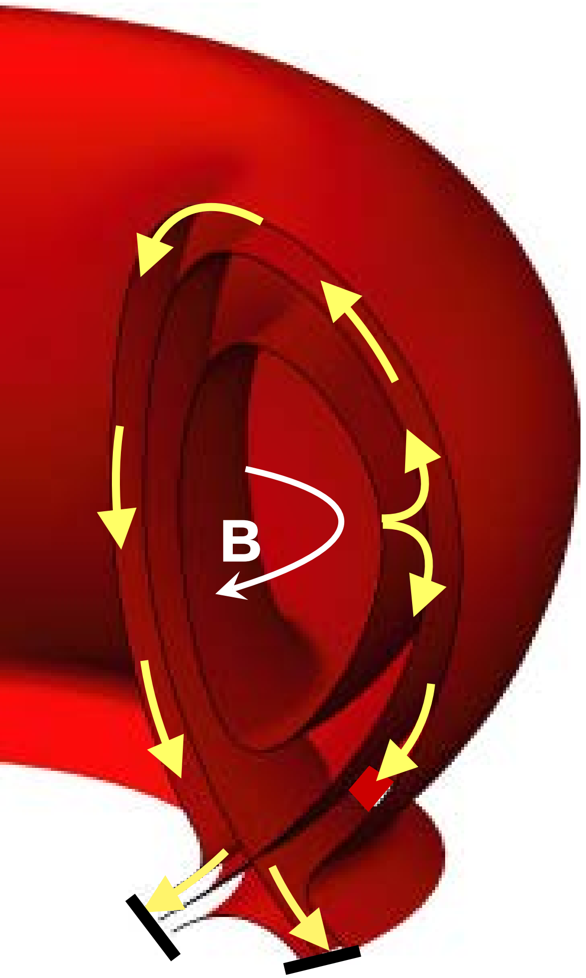


Fusion reaction releases energy

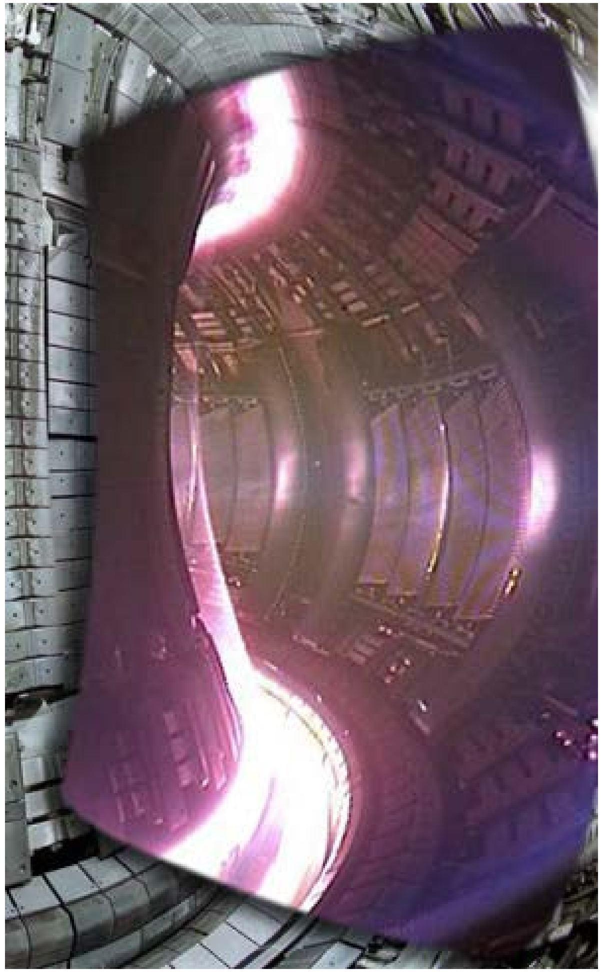


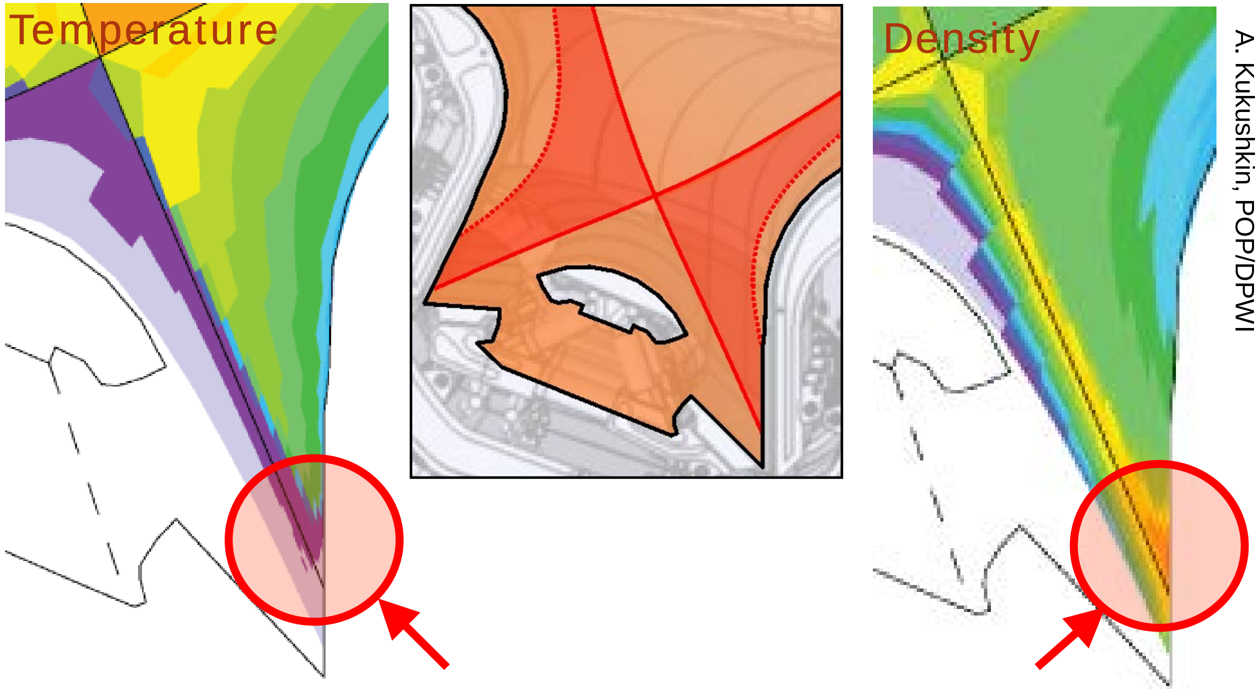
The tokamak is used to confine the plasma and reach required temperatures and confinement

The heat exhaust challenge in fusion



Divertor





A. Kukushkin, POP/DPWI

Low temperature (T_e~1 eV)

High density (n_e~10^{20} m^{-3})

Heat

10MW.m^{-2} steady-state

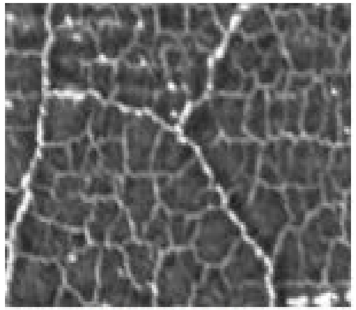
+

Particles

10^{24} $m^{-2}s^{-1}$ (10^5A.m^{-2})

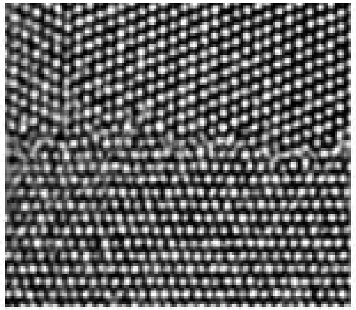
Solid vs. liquid metal PFCs

Solids:

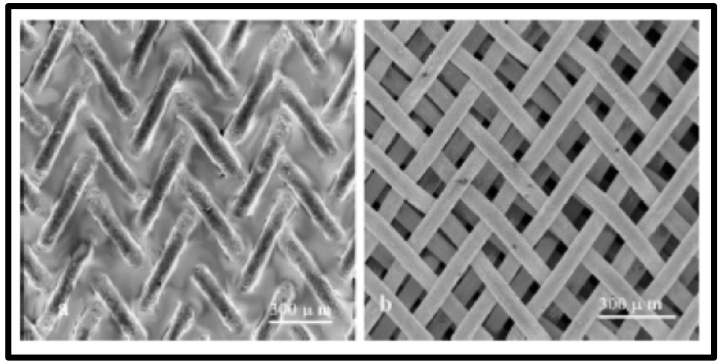

cracking


erosion


melting

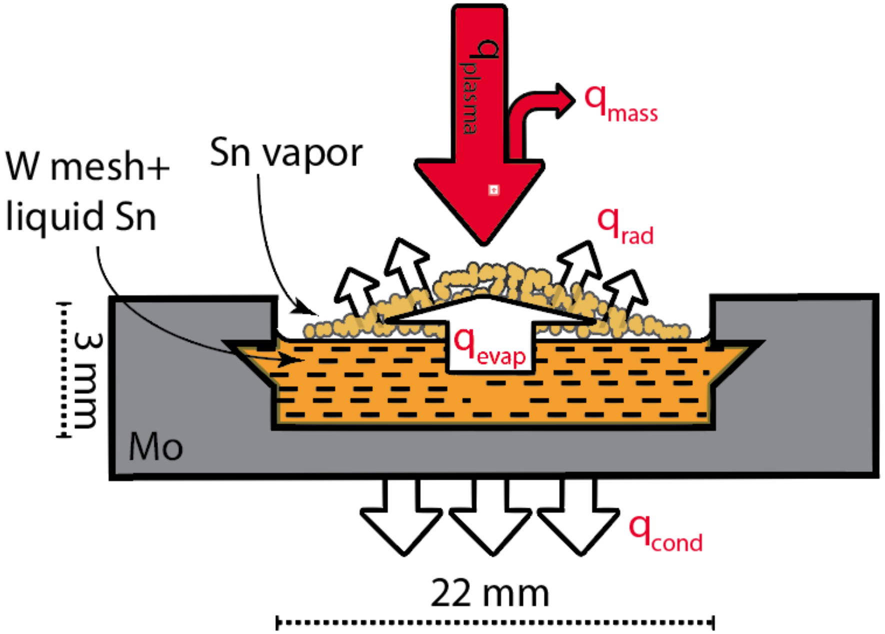

embrittlement

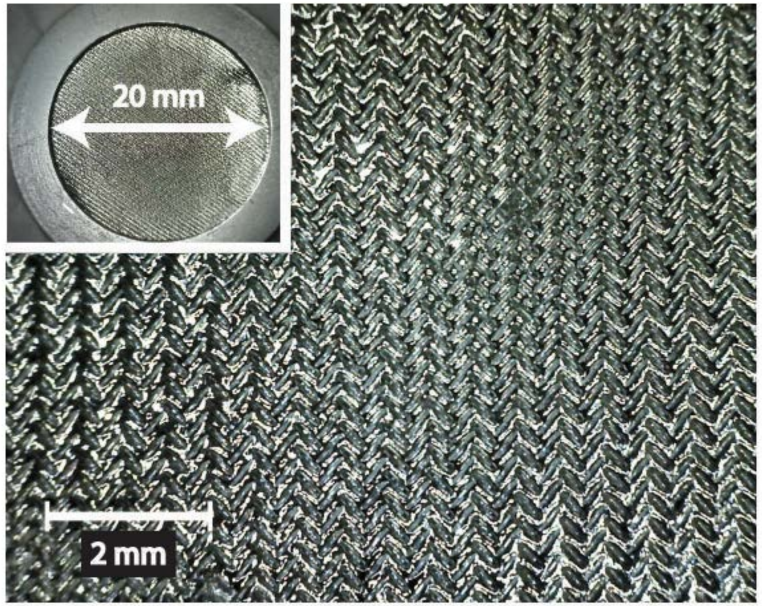
Liquids:



- Separates neutron issues from PSI issues
- Additional heat dissipation channels
- Sacrificial layer in case of loss of control
  → Power dissipation via evaporation/radiation
- **Prospect of continuous vapor shielding**
- But, limited experience and lots of unknowns…
- Technical more challenging

Vapour shielding: additional loss channels for heat flux

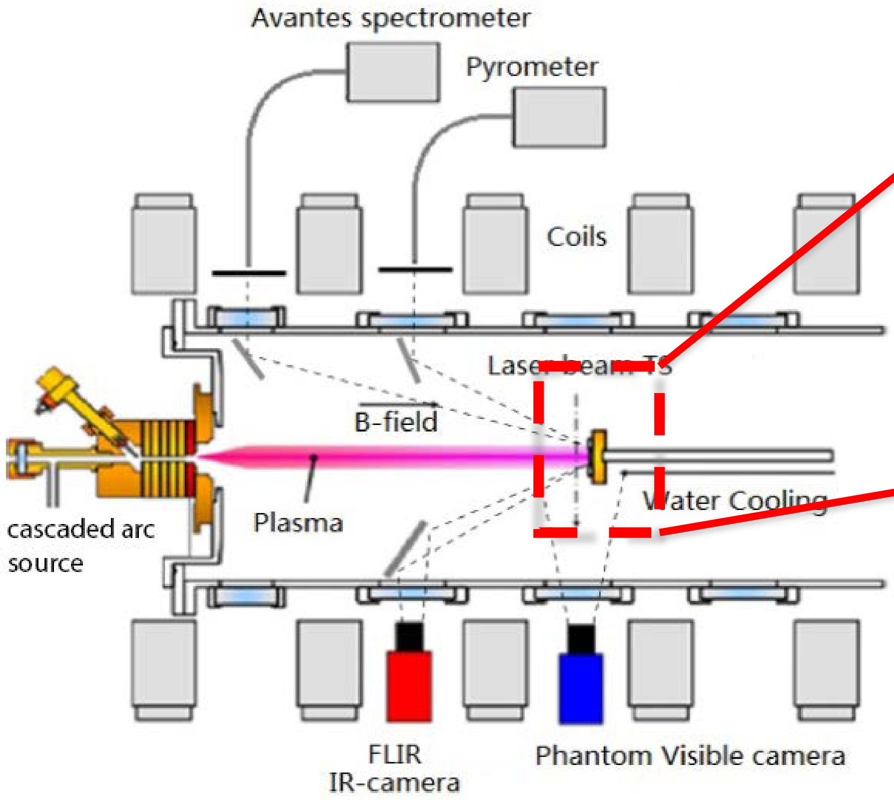


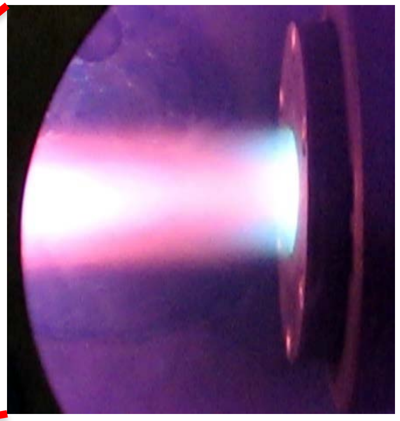


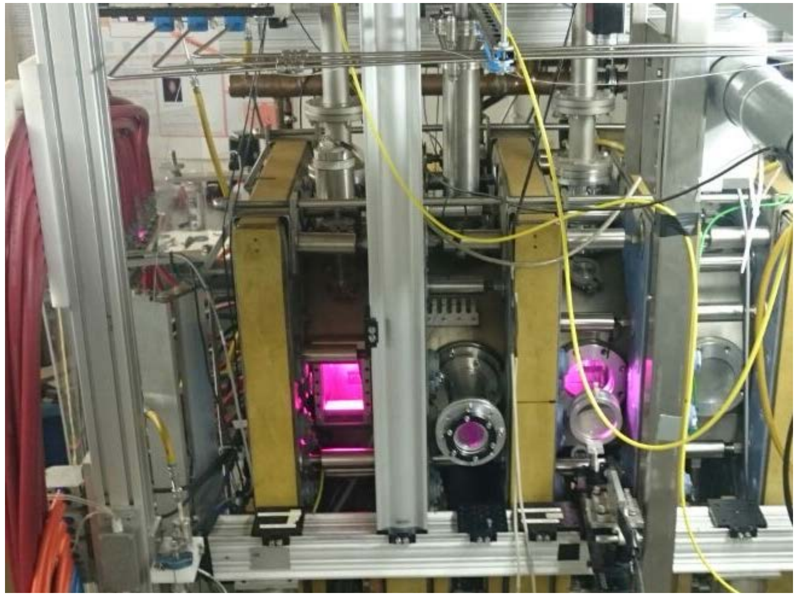
Solid metal: $q_{plasma} = q_{cond}$

Liquid metal: $q_{plasma} = q_{cond} + q_{evap} + q_{rad} + q_{mass}$

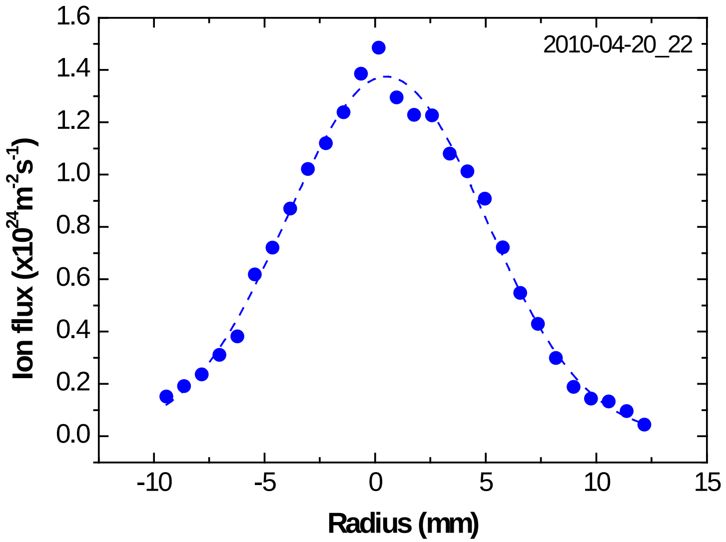
Exposure of liquid Sn and solid Mo samples to wide range of heat fluxes in Pilot-PSI linear device





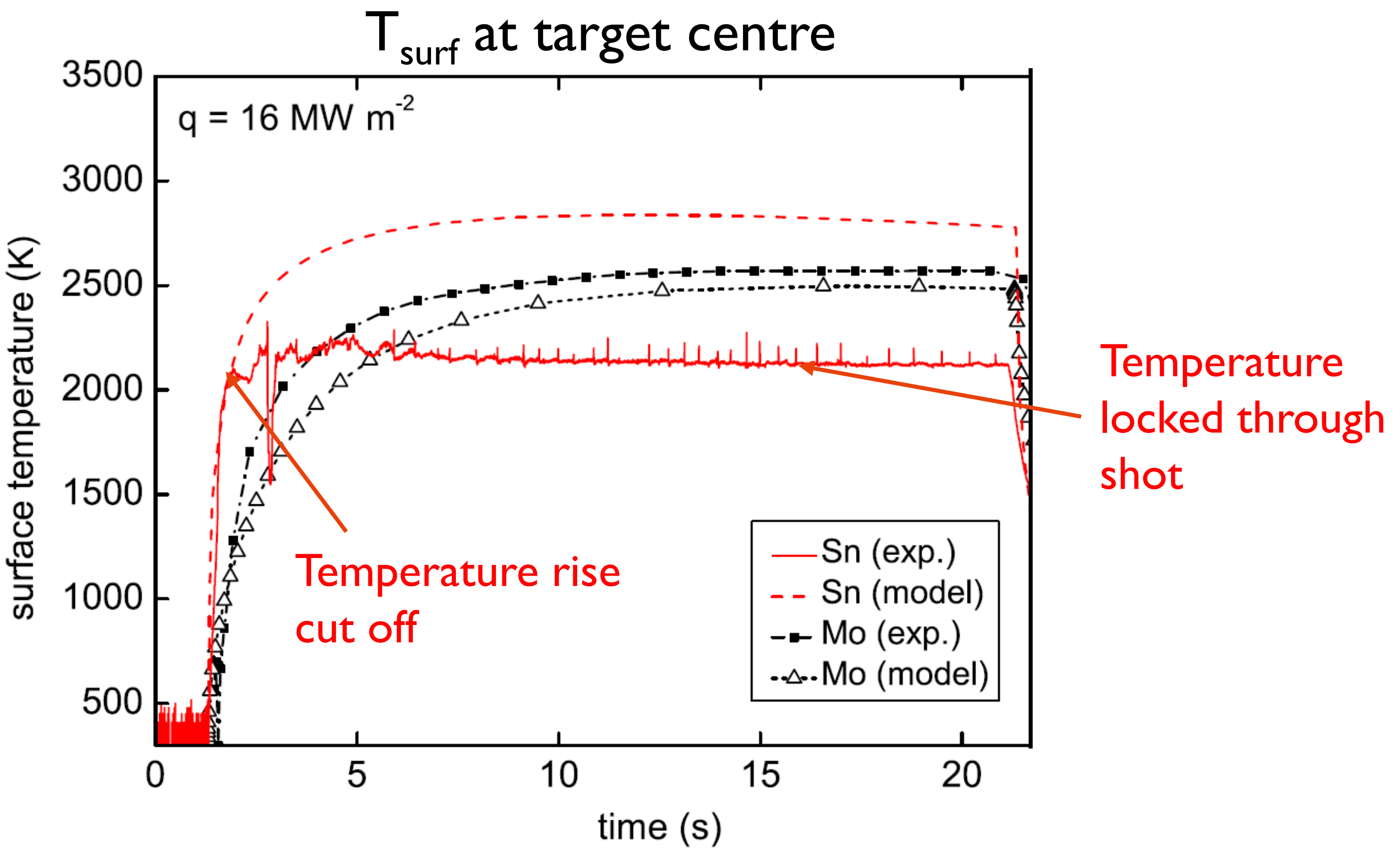


Gas	B-field (T)	Particle flux ($x10^{24}$ m^{-2} s^{-1})	Heat flux (q_{ref}) (MW m^{-2})
He	0.4-0.8	2.0-6.4	2.5-22.0
H	0.4-0.8	0.9-6.1	0.5-8.0



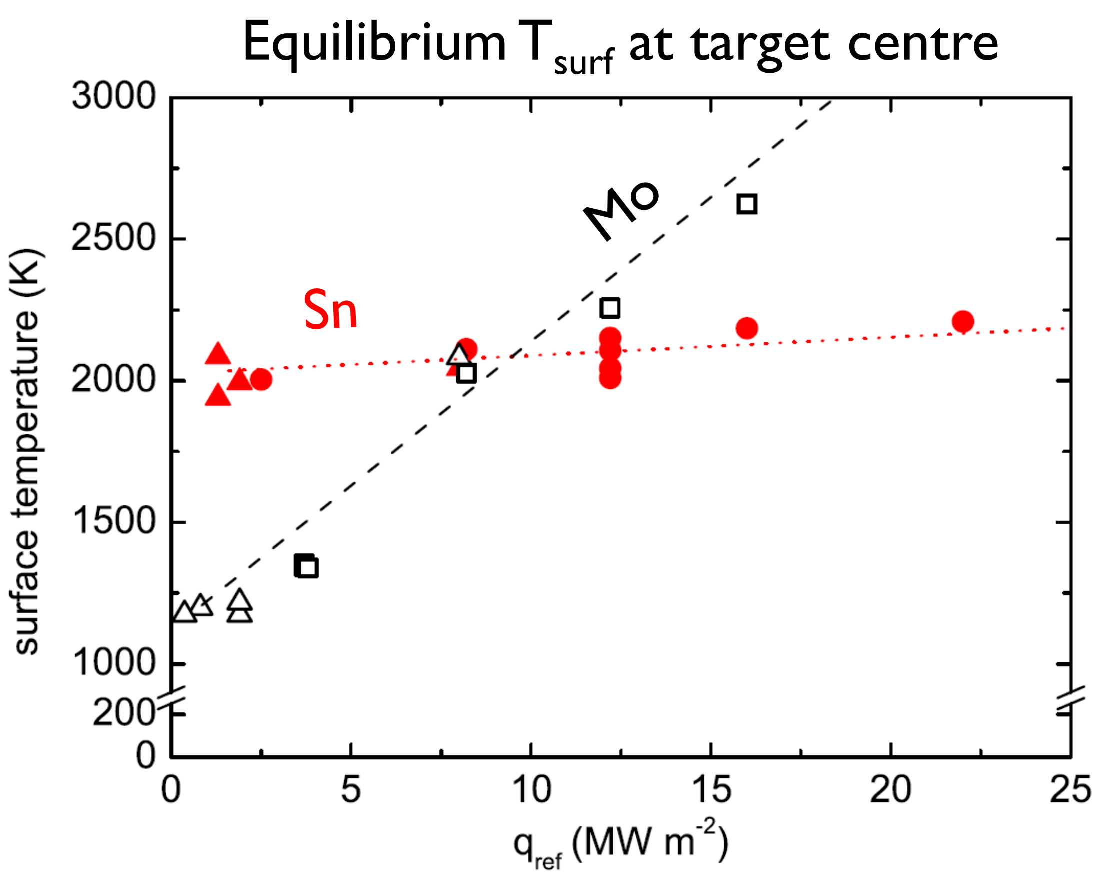
Vapour interaction with plasma decouples input power from surface temperature

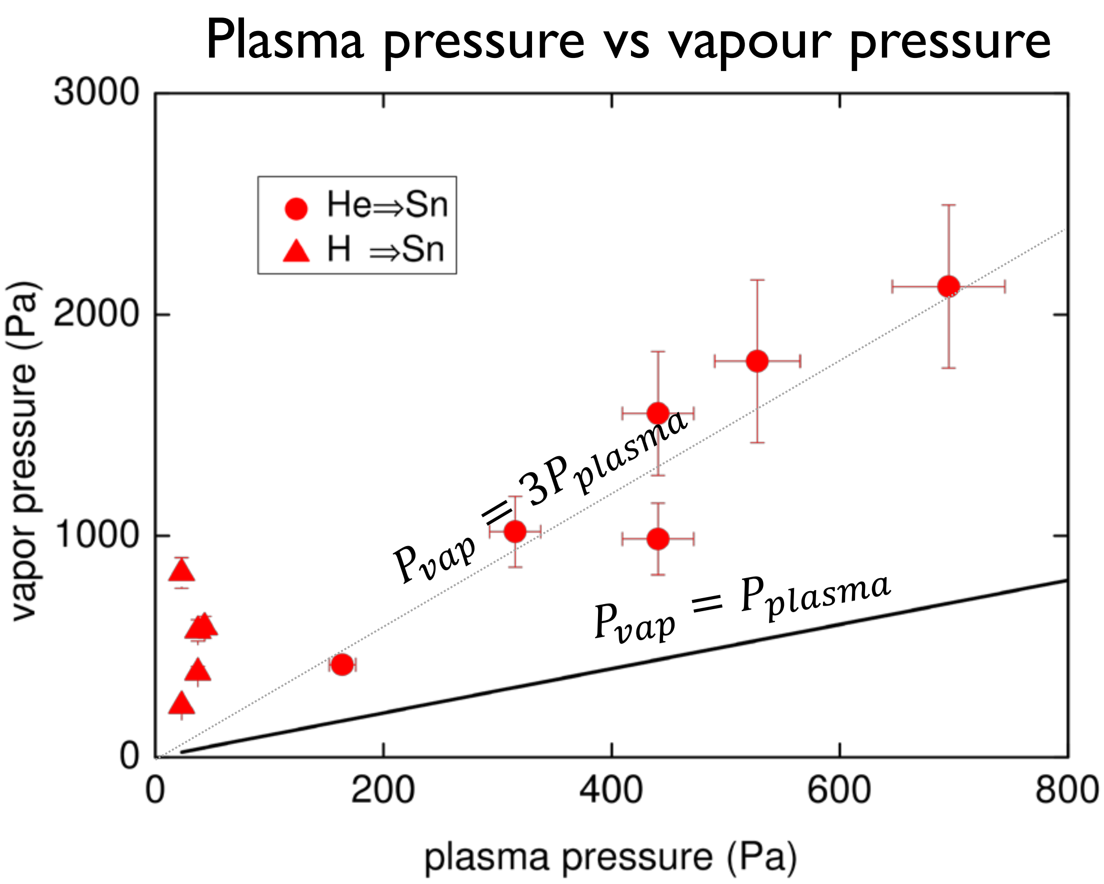
Poorly cooled Sn samples exposed to power load series in pilot-PSI



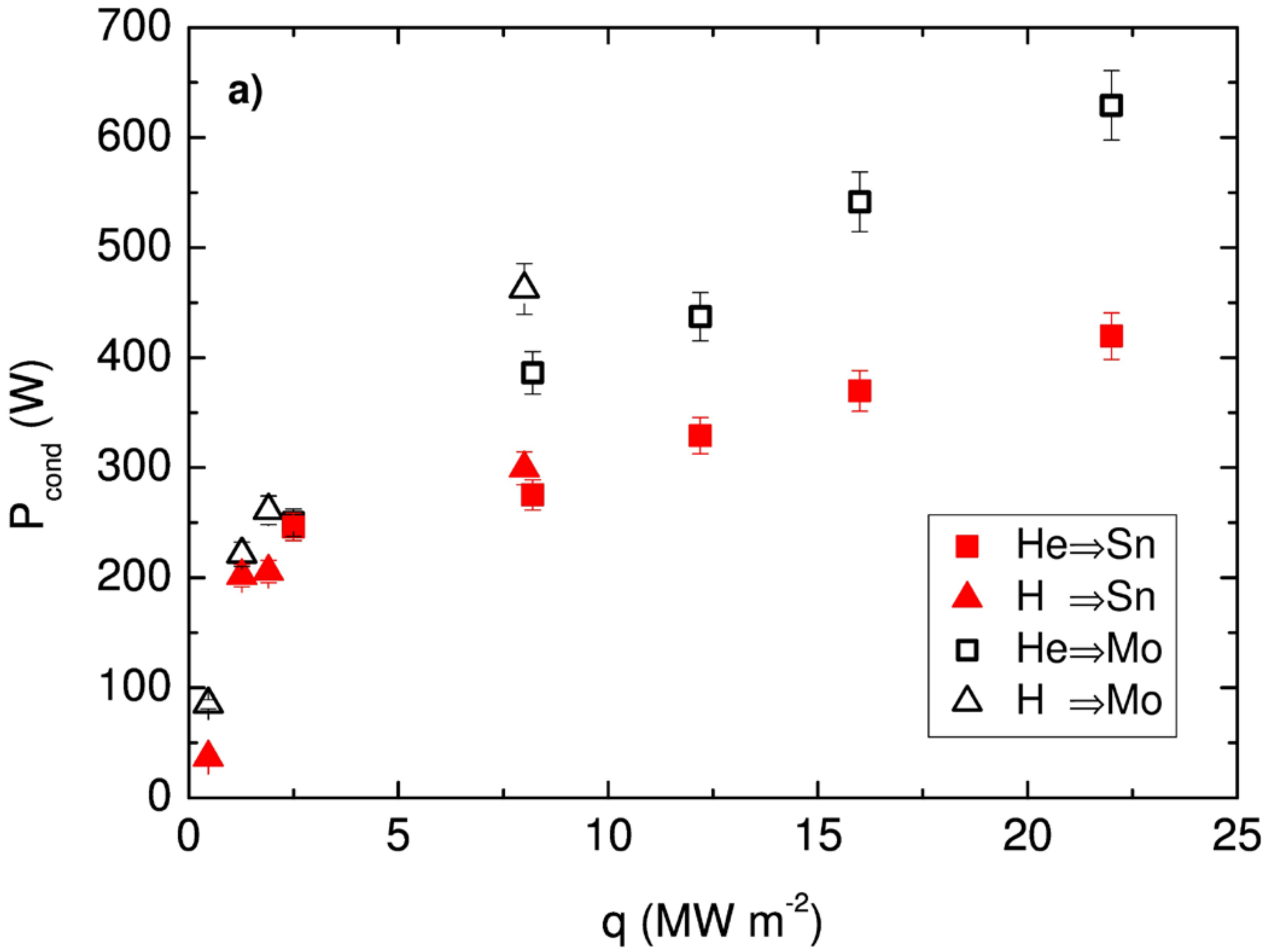
van Eden PRL 2016

Temperature locking when vapour pressure and plasma pressure ~ matches



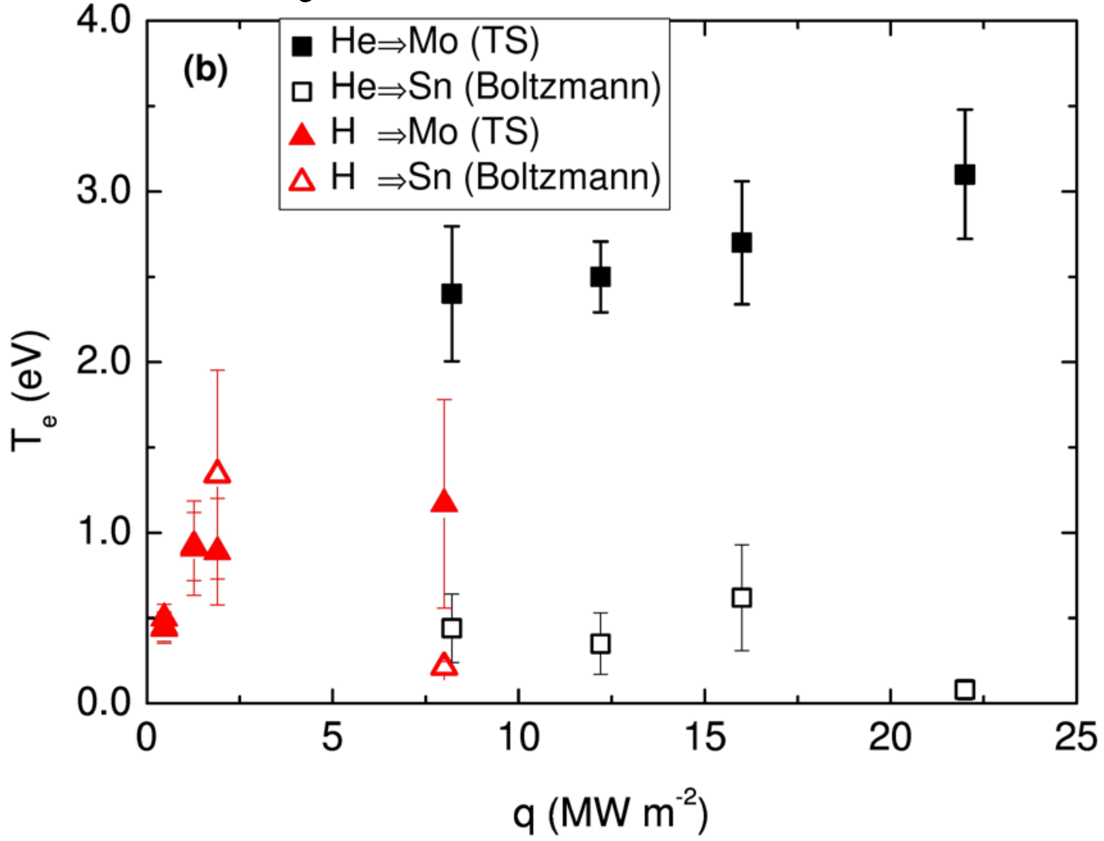


Overall reduction in power to cooling water of ~one third

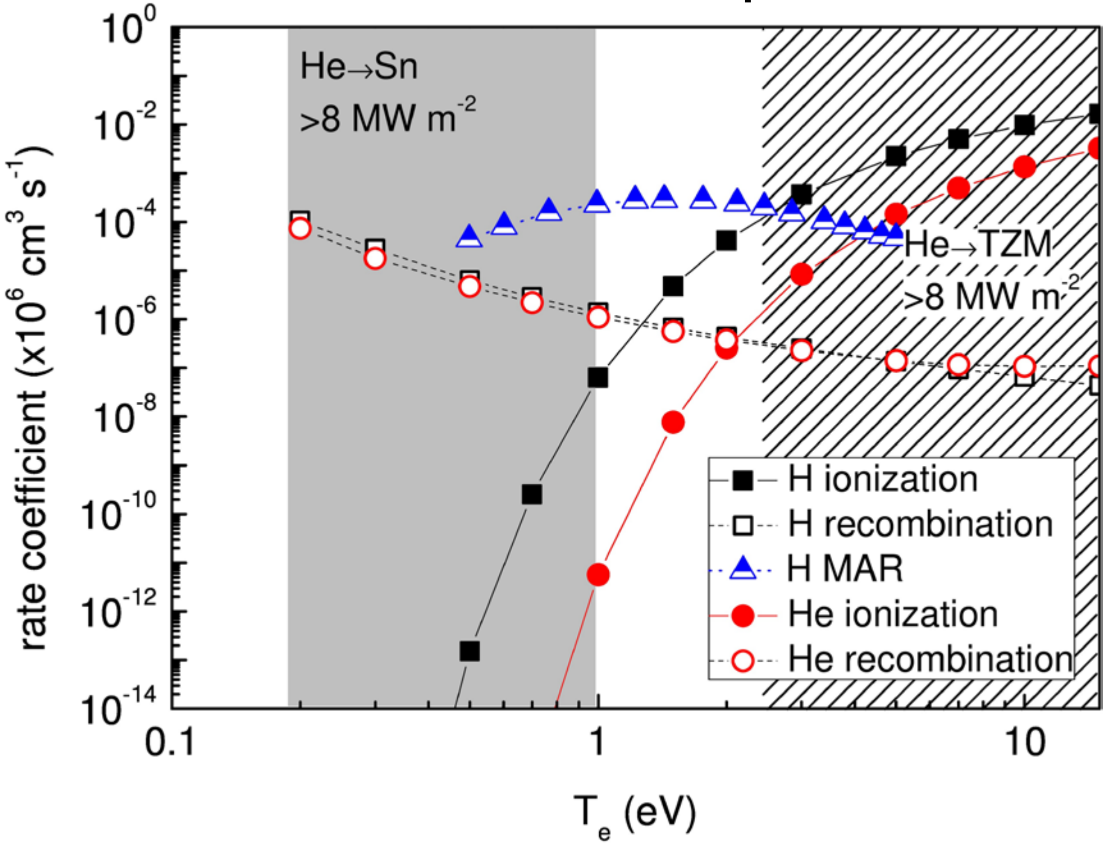


Strong recombination occurs due to lowered T_e

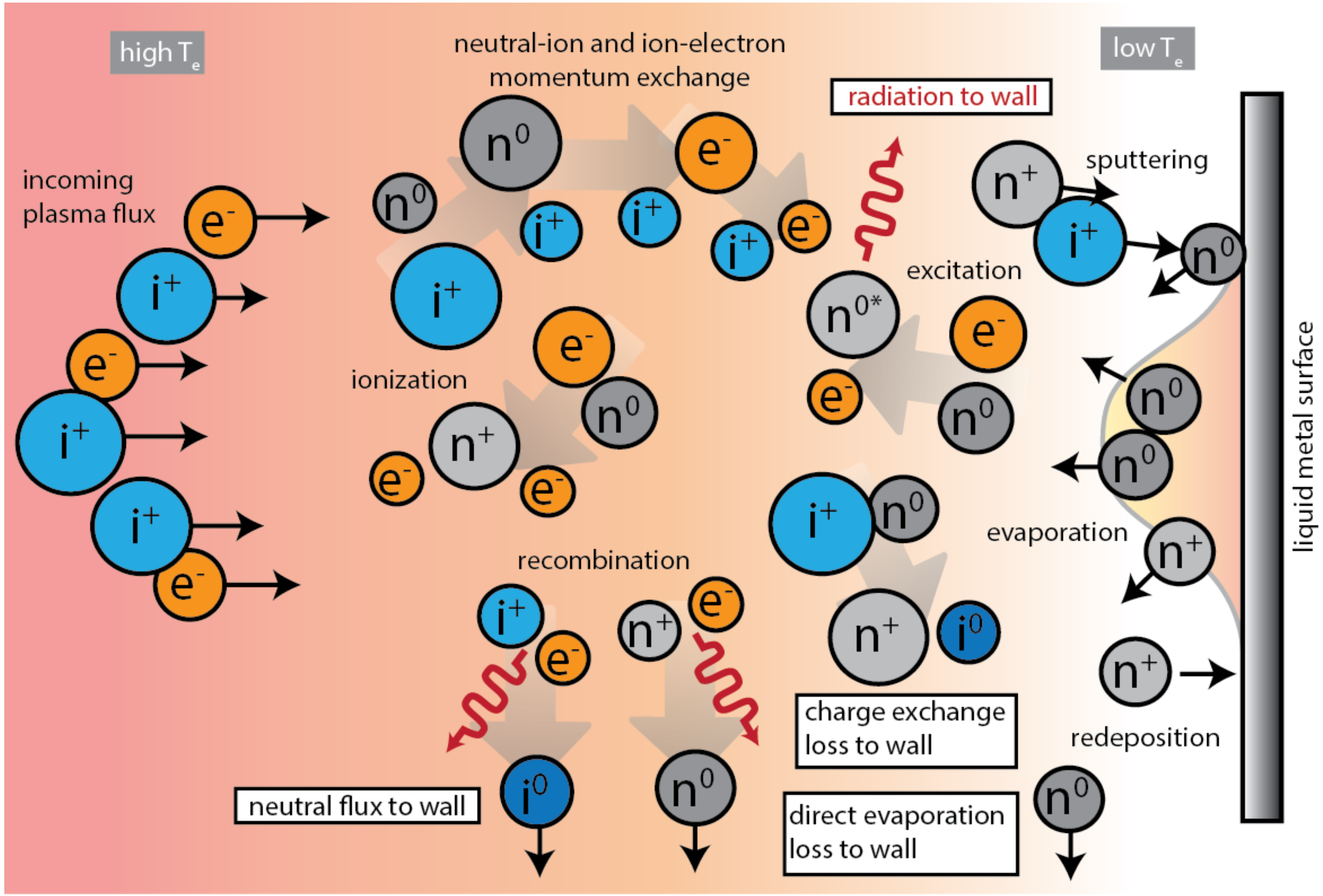
T_e Sn shots vs Mo shots



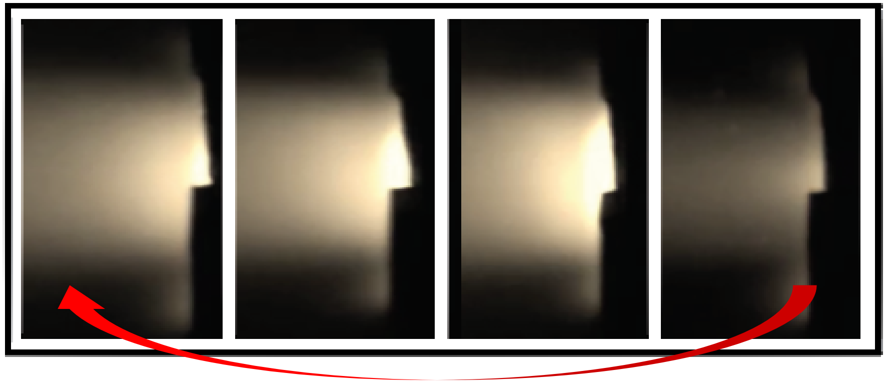
Atomic/Molecular processes



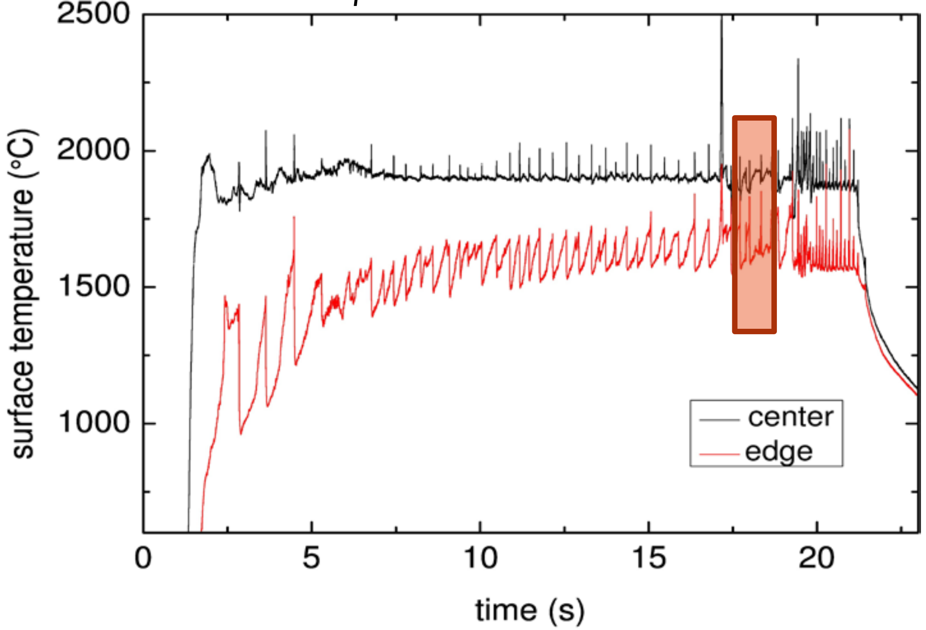
Atomic processes lead to mass loss and radiation away from surface of Sn sample



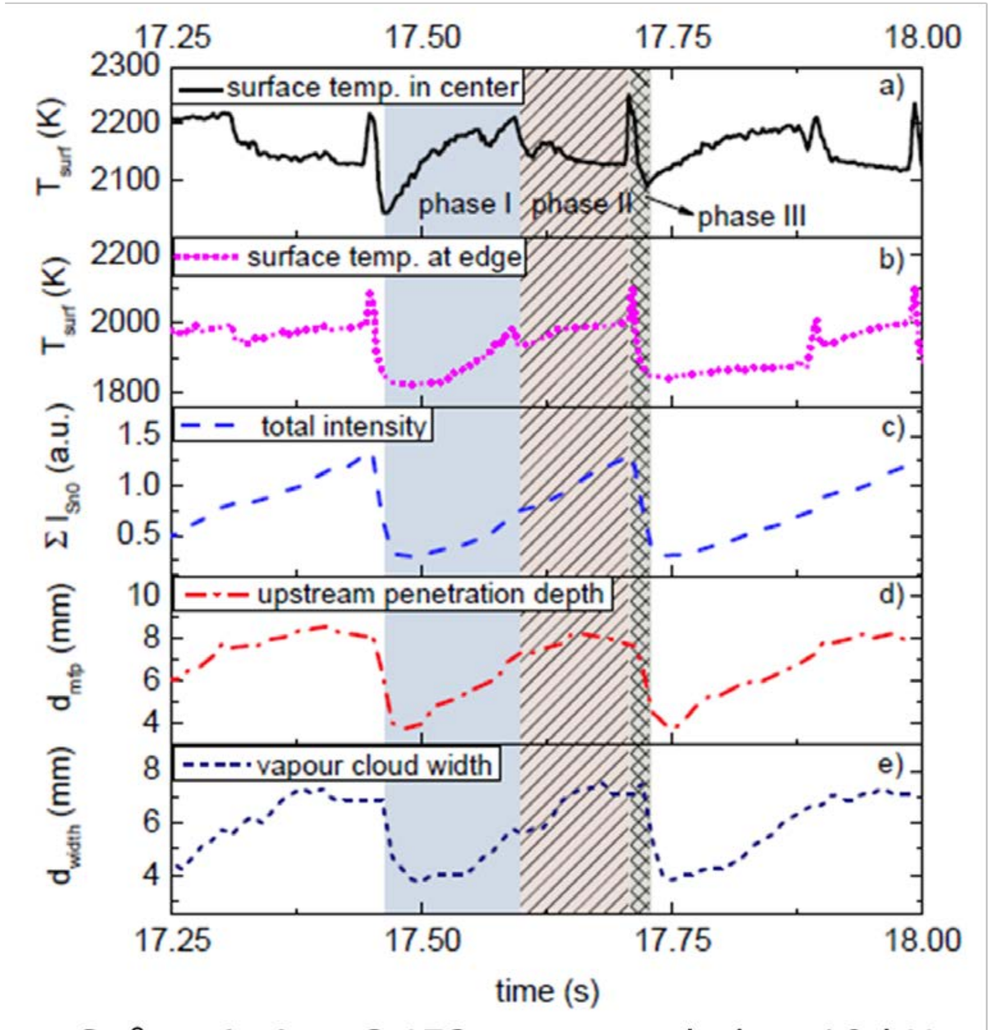
Shielding behaviour is oscillatory in nature



T_{surf} centre and edge

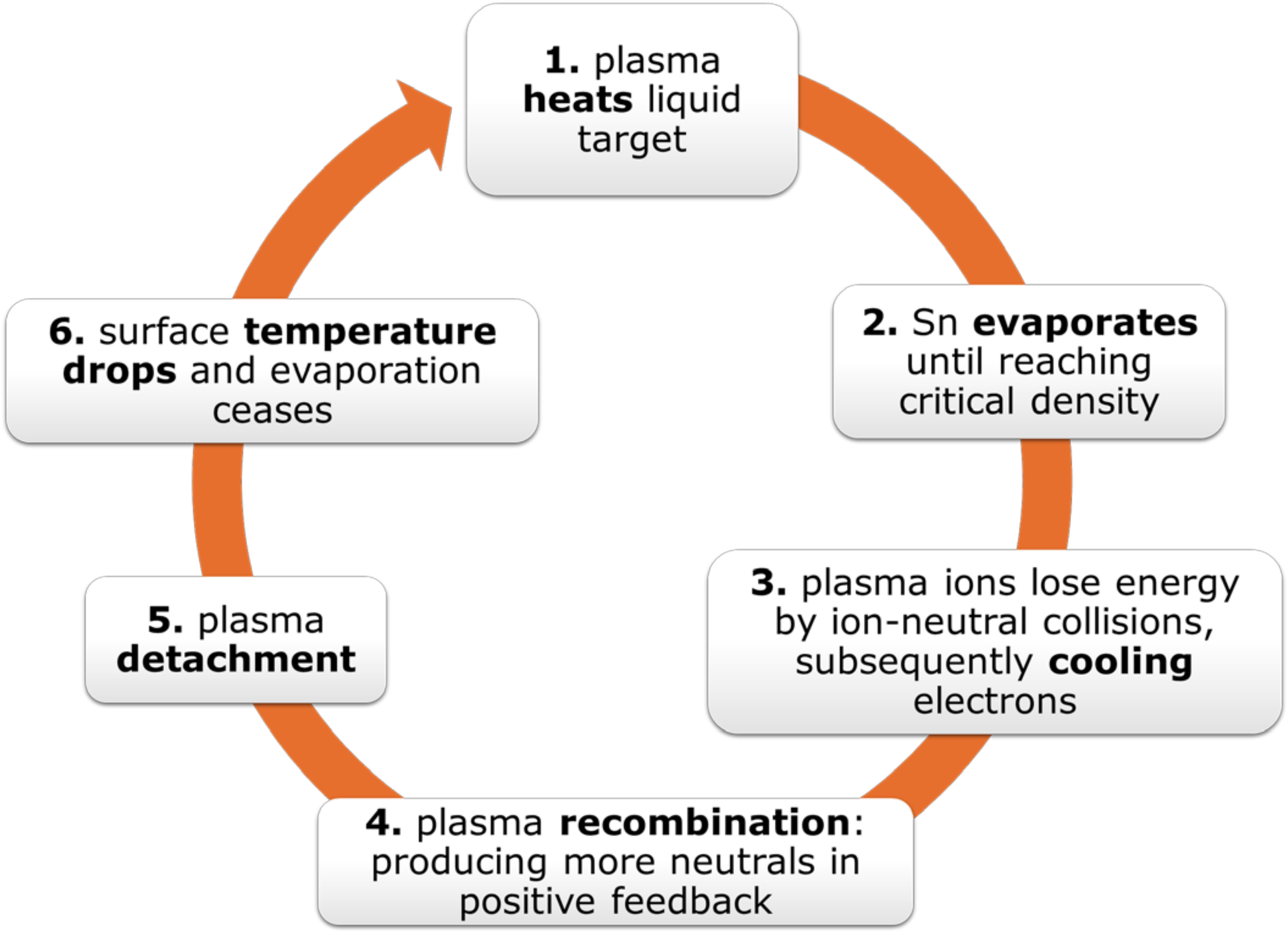


Emission and surface temp. correlated:

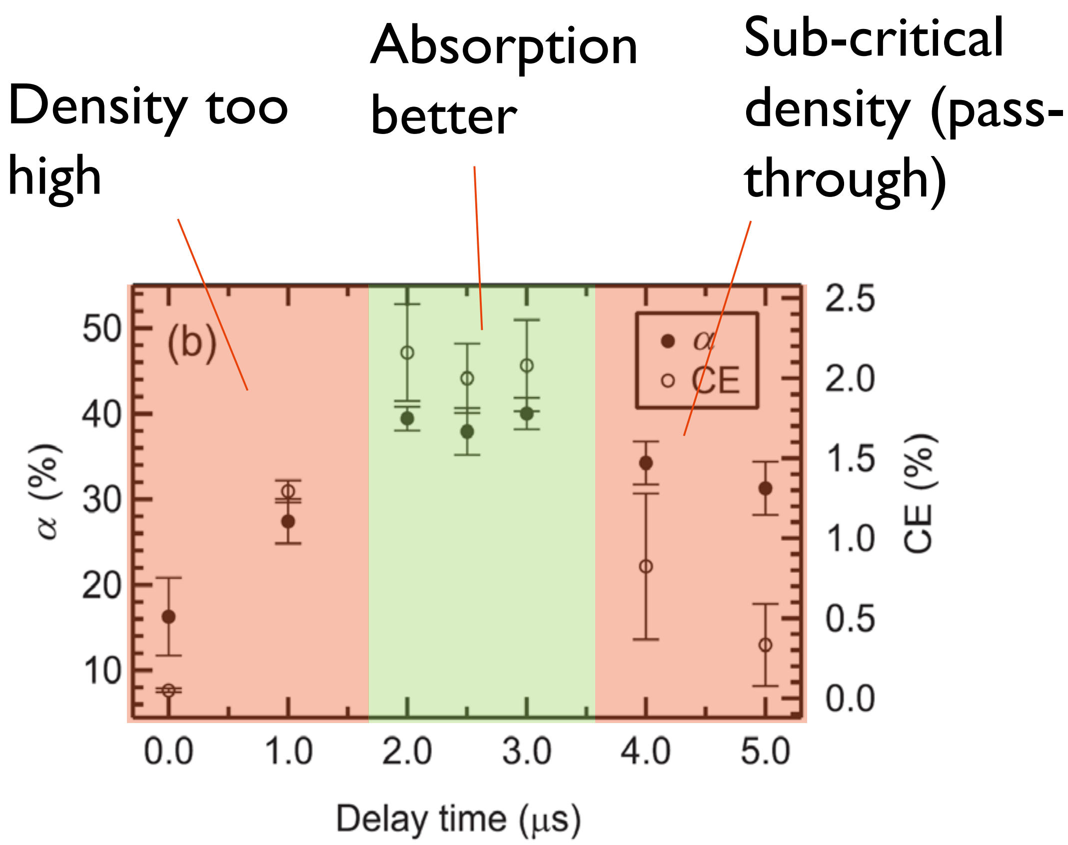


Sn^0 emission @452 nm recorded at 10 kHz

Cyclical equilibrium leads to dynamic locking of temperature at pressure balance point



Implications for EUV-plasma



Matsukuma APL (2015)

- Can a similar process occur in EUV source?
- Situations are dissimilar:
  - n_e and T_e higher
  - transient interaction
  - plasma-liquid interaction
- However, analogous is the saturation in absorption rate of CO_2 laser: when density is above cut-off limits transfer of energy to tin (outer layer of vapour prevents transfer of energy to inner layer)

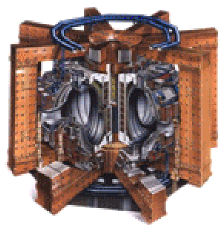
Conclusions

- Vapour shielding is effective in reducing heat load to target surface
- Plasma cooling by Sn atoms leads to reduction in incoming heat load, predominantly by radiation, CX and ion-neutral friction leading to recombination
- Processes dissimilar in EUV LPP Sn source, but similar principles at work in blocking full energy absorption

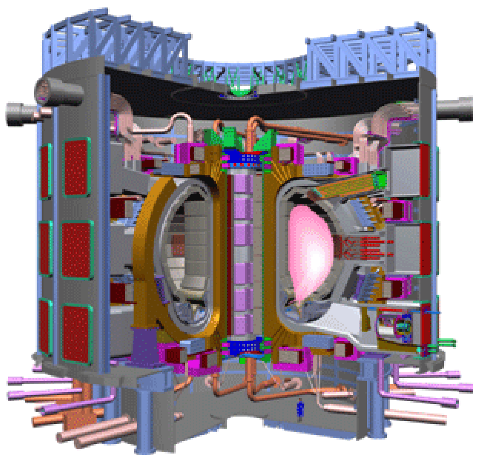
RESERVE SLIDES

The path to fusion power

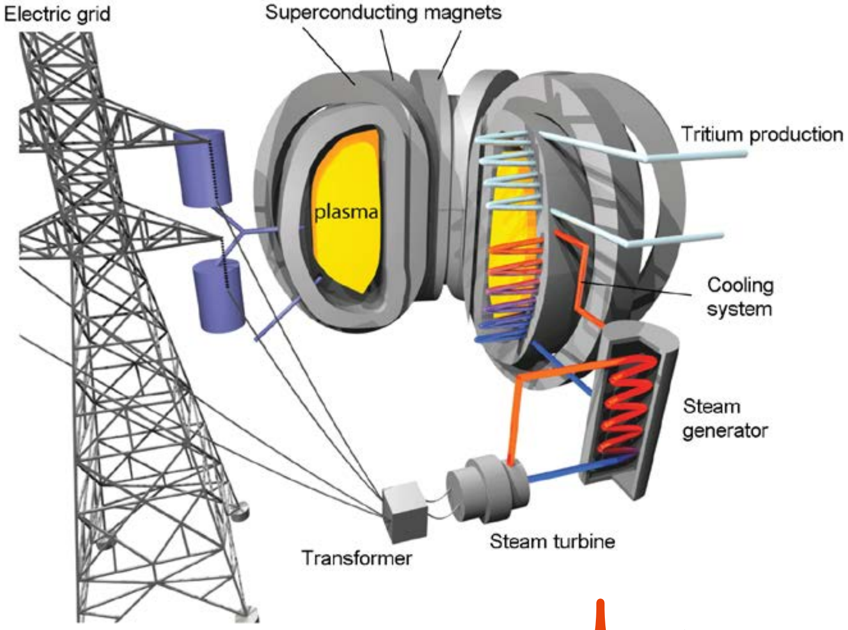
JET (to scale)



ITER



DEMO



2010 2020 2030 2040 2050 2060

- Q=0.5
- Understanding physics
- Preparation for ITER

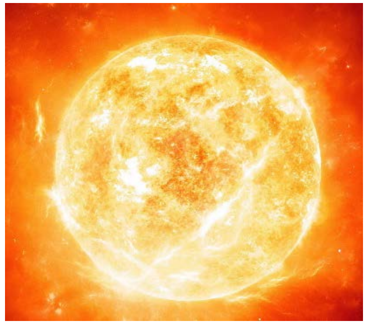
- Q=5-10
- Demonstrate fusion power
- Understanding engineering
- Preparation for DEMO

- Q~30
- Demonstrate power plant
- Prepare for wide-scale deployment

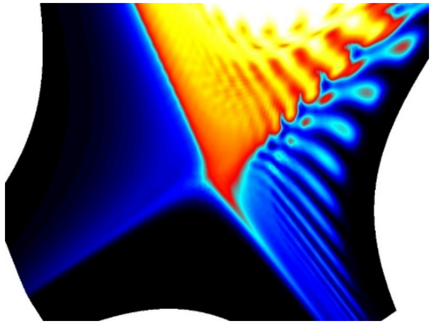
How much heat is that?

~1 kW m^{-2}
(~3 minutes)

~1 MW m^{-2}
(a few minutes)



63 MW m^{-2}
(4.6 billion years so far)



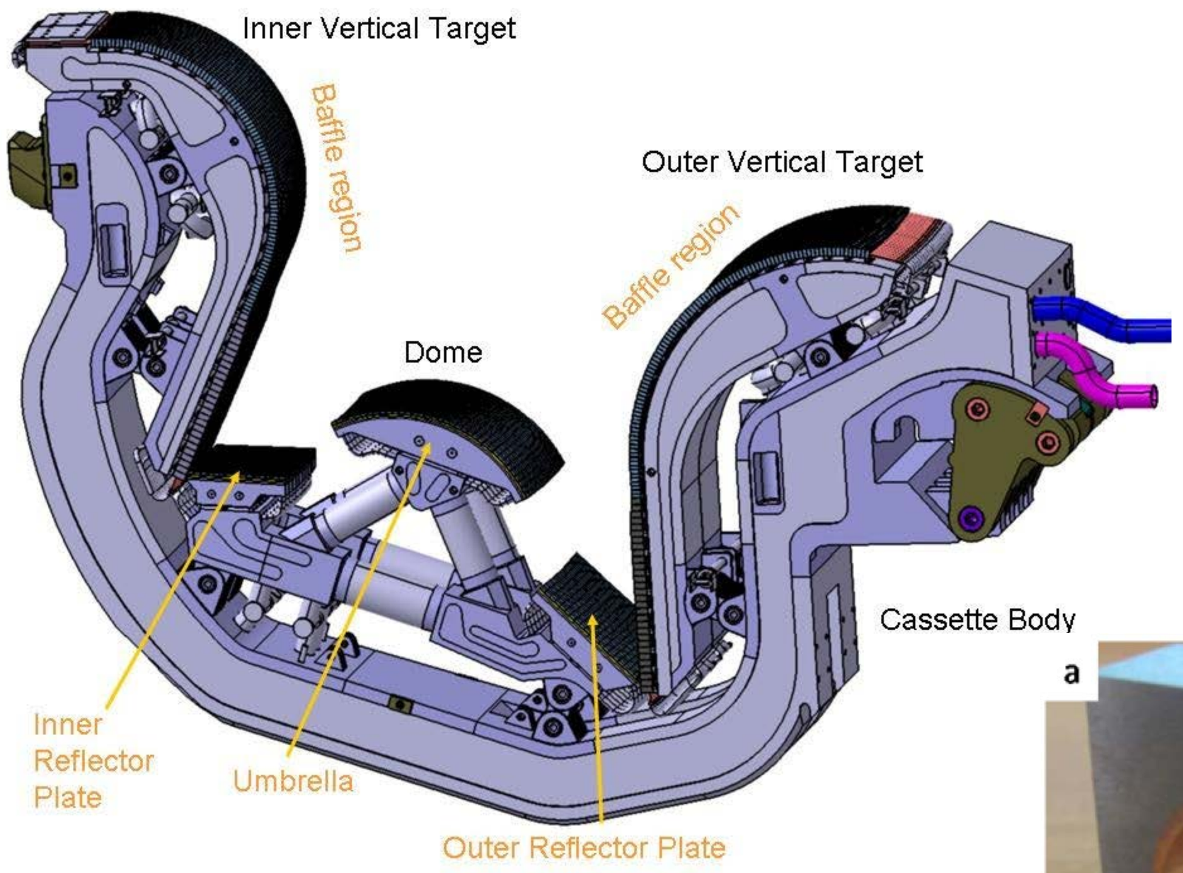
1 GW m^{-2}
(1 ms x millions of times)

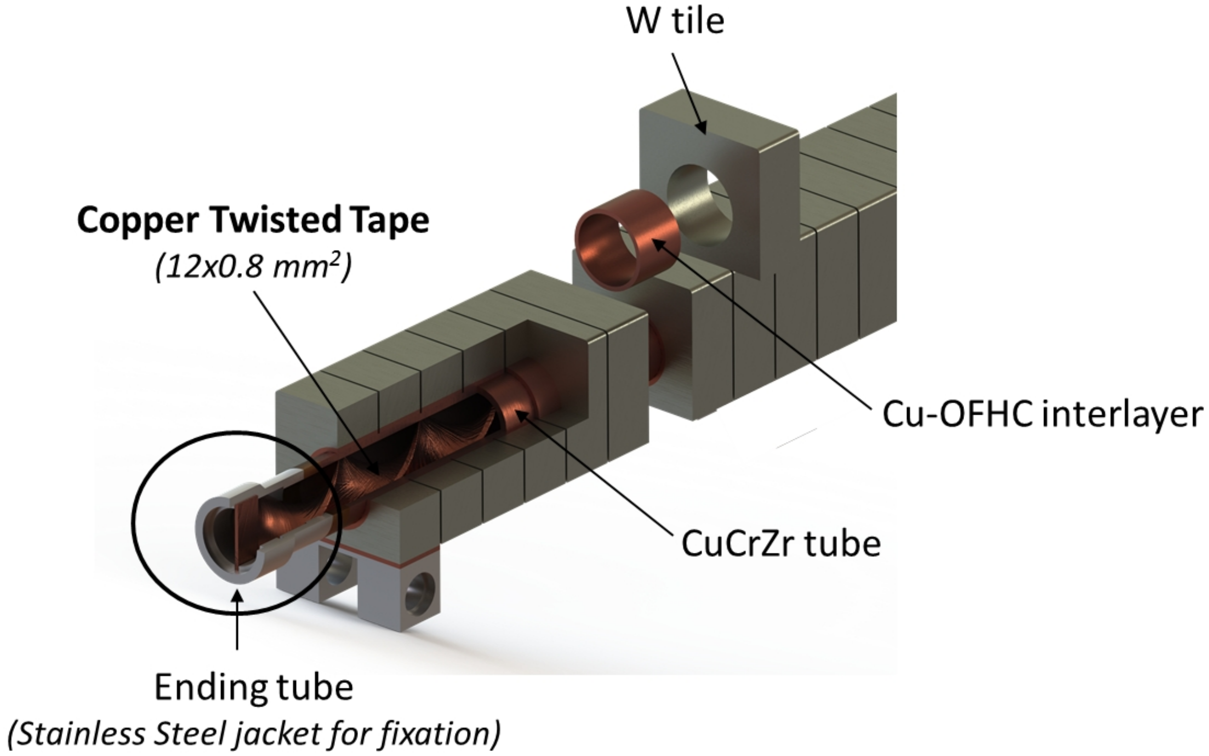
Few 100 kW m^{-2}
(take-off/landings)

~10 MW m^{-2}
(~5 years)

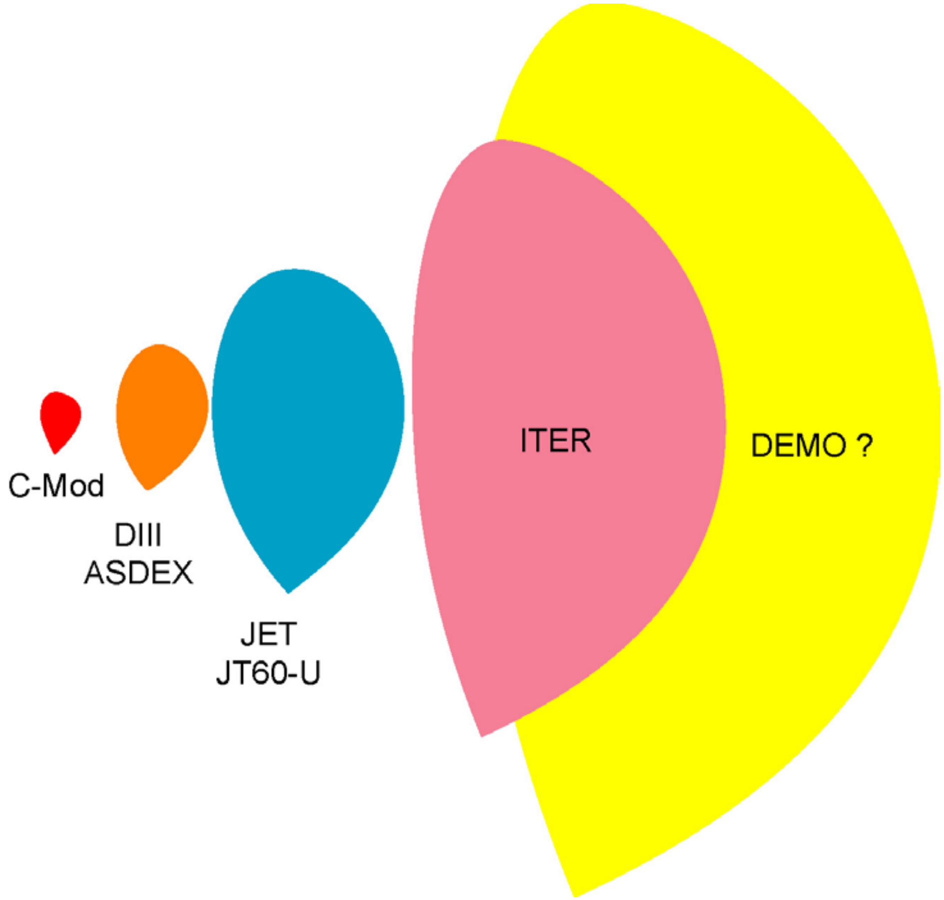
~80 MW m^{-2}
(~2 minutes)

The solution for ITER





Going from ITER to DEMO involves large jumps in several parameters



Courtesy G. Matthews

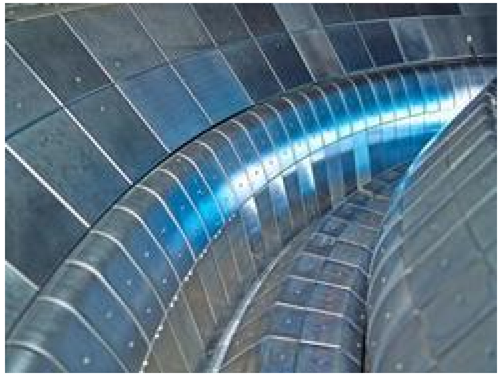
- Timescales/fluence much larger
- Neutron loading much higher
- Narrow path to avoid excessive exhaust power

Property	ITER	DEMO[1]
Pulse length	~400 s	~7200 s
Duty cycle	**<2%**	**60-70%**
Neutron load	**0.05 dpa/yr**	**1-9 dpa/yr**
Exhaust power	150 MW	500 MW
Divertor area	~4 m^2	~6 m^2
Radiated power	**80%**	**97%**

Limiting factors for W in DEMO

Neutrons

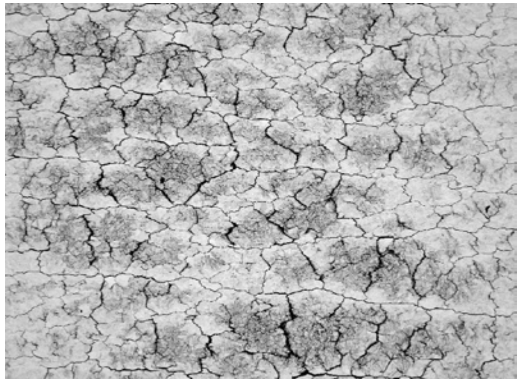
High heat/particles



Erosion

For 5 mm W lifetime ~2 years[1]

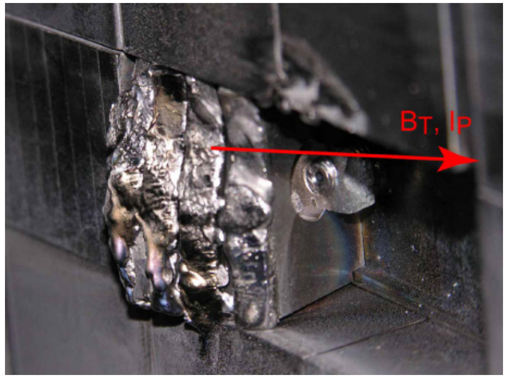
Thermal shock/fatigue



Cracking (small ELM-like loading)[2]

Progressive deterioration[3]

Big ELMs/VDEs/disruptions



Melting- irreversible damage

Runaway failure?

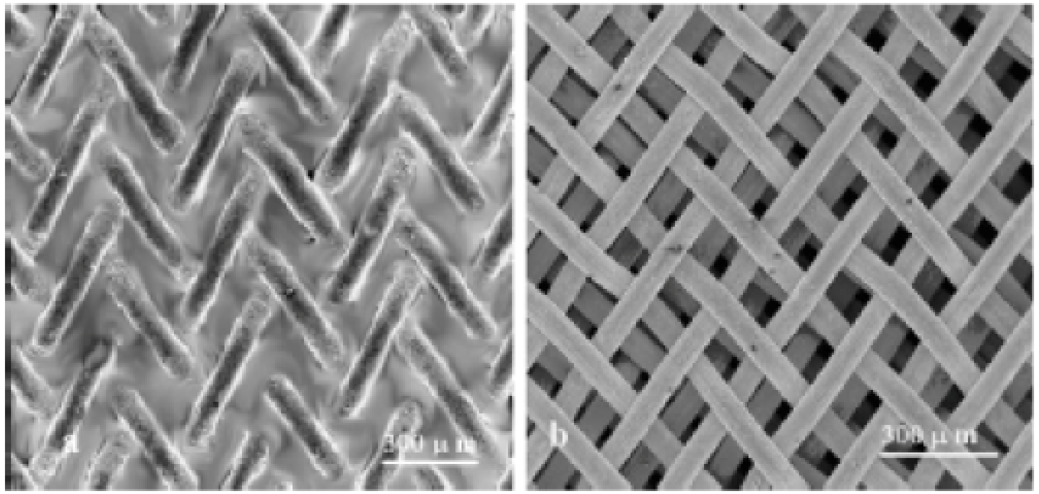
Transmutation, H+He creation, defects

Smaller operational temperature window

Increased brittleness

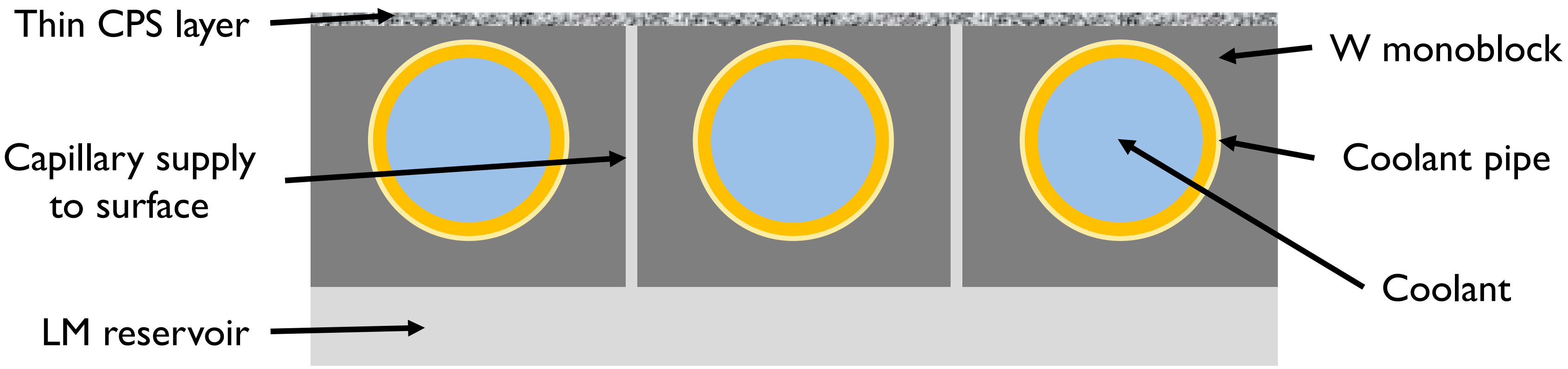
[1] Maissonier NF 2007
[2] Linke NF 2011
[3] Loewenhoff FED 2012

Capillary porous structures (CPSs) create conduction based stabilized PFCs



Evtikhin 1999

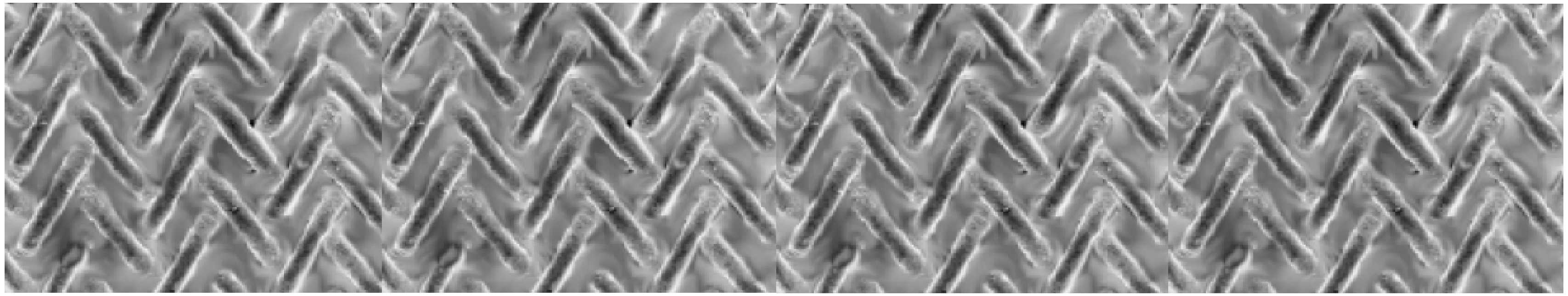
- Replace solid surface with liquid
- MHD forces (j x **B**) destabilize liquids in tokamaks (droplets)
- Use surface tension/capillary refilling
- Replace top region with this combined material



Benefits of liquid metals for DEMO

Neutrons

Sputtering | Thermal shock/fatigue | Big ELMs/VDEs/disruptions



Self replenishment

Higher heat fluxes

(see later)

No cracking

Lowered stresses substrate

ELMs possible(?)

Already molten

Vapour protection

(see later)

Only influences substrate

Separation of PSI from neutron issue